Effects of different ridge-furrow mulching systems on yield and water use efficiency of summer maize in the Loess Plateau of China

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Abstract: Ridge-furrow film mulching has been proven to be an effective water-saving and yield-improving planting pattern in arid and semi-arid regions. Drought is the main factor limiting the local agricultural production in the Loess Plateau of China. In this study, we tried to select a suitable ridge-furrow mulching system to improve this situation. A two-year field experiment of summer maize (*Zea mays* L.) during the growing seasons of 2017 and 2018 was conducted to systematically analyze the effects of flat planting with no film mulching (CK), ridge-furrow with ridges mulching and furrows bare (RFM), and double ridges and furrows full mulching (DRFFM) on soil temperature, soil water storage (SWS), root growth, aboveground dry matter, water use efficiency (WUE), and grain yield. Both RFM and DRFFM significantly increased soil temperature in ridges, while soil temperature in furrows for RFM and DRFFM was similar to that for CK. The largest SWS was observed in DRFFM, followed by RFM and CK, with significant differences among them. SWS was lower in ridges than in furrows for RFM. DRFFM treatment kept soil water in ridges, resulting in higher SWS in ridges than in furrows after a period of no water input. Across the two growing seasons, compared with CK, RFM increased root mass by 10.2% and 19.3% at the jointing and filling stages, respectively, and DRFFM increased root mass by 7.9% at the jointing stage but decreased root mass by 6.0% at the filling stage. Over the two growing seasons, root length at the jointing and filling stages was respectively increased by 75.4% and 58.7% in DRFFM, and 20.6% and 30.2% in RFM. Relative to the jointing stage, the increased proportions of root mass and length at the filling stage were respectively 42.8% and 94.9% in DRFFM, 63.2% and 115.1% in CK, and 76.7% and 132.1% in RFM, over the two growing seasons, showing that DRFFM slowed down root growth while RFM promoted root growth at the later growth stages. DRFFM treatment increased root mass and root length in ridges and decreased them in 0–30 cm soil layer, while RFM increased them in 0–30 cm soil layer. Compared with CK, DRFFM decreased aboveground dry matter while RFM increased it. Evapotranspiration was reduced by 9.8% and 7.1% in DRFFM and RFM, respectively, across the two growing seasons. Grain yield was decreased by 14.3% in DRFFM and increased by 13.6% in RFM compared with CK over the two growing seasons. WUE in CK was non-significantly 6.8% higher than that in DRFFM and significantly 22.5% lower than that in RFM across the two growing seasons. Thus, RFM planting pattern is recommended as a viable water-saving option for summer maize in the Loess Plateau of China.

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1 Introduction

The dryland agriculture in the Loess Plateau is an important part of China's agriculture. However, due to the influence of the temperate monsoon climate and the temperate continental climate, the precipitation is low and mainly occurs in July–September in this region. Most of the precipitation is multiple light rain and infrequent heavy rain (Chen et al., 2015), which cannot be effectively used by summer maize that is widely grown in this region. The resulting drought and soil erosion have seriously hindered the sustainable development of local agriculture (Gu et al., 2019; Feng et al., 2020). Unavailable precipitation to crops and inconsistency between precipitation distribution and critical period of crop water demand are the main causes of drought in local summer maize production. In addition, population growth and industrial development have also exacerbated the excessive use of surface water and groundwater. The gap between agricultural water supply and water use will widen (Gu et al., 2018). In order to deal with the problem of agriculture drought, one of the effective ways is to improve the utilization efficiency of precipitation in this region.

Ridge-furrow with film mulching is regarded as an effective rainwater harvesting planting pattern in arid and semi-arid regions (Yin et al., 2018; Gu et al., 2020). For ridge-furrow with ridges mulching and furrows bare (RFM) planting pattern, the mulched ridges serve as rainwater collection areas and the bare furrows serve as rainwater infiltration and planting areas. RFM planting pattern can collect light rain, increase the availability of light rain and water infiltration, and improve soil water storage (SWS) to meet immediate crop water requirements (Yin et al., 2015; Wang et al., 2016; Zhou et al., 2020). It also reduces soil evaporation, extends the time of soil water availability to crops, and eventually improves the controllability of rainfall resources in both time and space (Zhou et al., 2012; Gu et al., 2016; Yin et al., 2018). Based on the advantages mentioned above, RFM planting pattern has performed well in relieving crop drought and improving water use efficiency (WUE) and crop yield; it has been shown to be a useful method in arid and semi-arid regions (Eldoma et al., 2016; Wang et al., 2018; Zheng et al., 2020). In recent years, an improved planting pattern, double ridges and furrows full mulching (DRFFM) technology has emerged in Gansu Province and Ningxia Hui Autonomous Region, China (Wu et al., 2017). Because of the larger mulching area, DRFFM technology does a better job on collecting light rain, increasing soil moisture, reducing soil evaporation, and raising soil temperature. In addition, due to the narrower furrows, the collected rainwater is concentrated in the planting row for crop absorption. DRFFM technology has been shown to significantly improve grain yield and WUE for maize (Liu et al., 2014; Ren et al., 2016), cotton (He et al., 2018; Wang et al., 2018), and potato (Wang et al., 2005; Zhao et al., 2014). Both RFM and DRFFM have achieved significant positive effects mainly in dry and cold regions (Zhang et al., 2019b).

However, in recent decades, with climate warming, the problems faced by the dry farming regions in the Loess Plateau have also changed (He et al., 2019). The local agriculture is not only facing with more severe droughts caused by temperature rising, but also confronting with earlier crop phenology, shorter growing seasons, and CO_2 emissions (Xiao et al., 2019; Feng et al., 2020). Some studies have also found that the yield-increasing effect of ridge-furrow with film mulching will diminish with the increases of precipitation and air temperature (Yu et al., 2018; Zhang et al., 2018). Qin et al. (2018) proposed that the choice of mulch should take into account the local climatic conditions. Whether these ridge-furrow mulching systems are still suitable for the dry farming regions in the Loess Plateau and which one dose better in improving local agricultural production need to be clarified. Ridge-furrow mulching systems greatly change the topsoil shape and soil aeration and especially have a different impact on the soil water and heat conditions in the ridges and furrows. The influence of soil hydrothermal conditions in ridges on crop growth should not be ignored. Previous studies have mainly focused on the effects of soil hydrothermal conditions

in furrows on crop yield and WUE but paid less attention to the changes of soil moisture and temperature in ridges (Wang et al, 2015; Wang et al, 2018). It is not enough to understand the impact of ridge-furrow mulching systems on agricultural production to only pay attention to the water and heat changes in furrows and ignore them in ridges.

Therefore, the objectives of this study were to: (1) assess the effects of different ridge-furrow mulching systems on soil temperature, SWS, root growth, aboveground dry matter, grain yield, and WUE; and (2) determine the suitability of RFM and DRFFM to the production of summer maize in dry farming regions of the Loess Plateau under current climate conditions.

2 Materials and methods

2.1 Study area

The experimental site is the irrigation station (34°18′N, 108°24′E) of Northwest A&F University, Yangling, located in Northwest China. This region has an annual mean air temperature of 12.9°C, a mean annual precipitation of 632 mm (about 70% during July–September), a mean annual pan evaporation of 1500 mm, a mean sunshine duration of 2164 h, and a frost-free period of more than 210 d. The topsoil (0.0–0.2 m) of the experimental field is loam, with the field capacity of 24.0%, permanent wilting point of 8.5%, dry bulk density of 1.40 g/cm^3, organic matter content of 13.36 g/kg, total nitrogen content of 0.96 g/kg, nitrate nitrogen content of 73.01 mg/kg, available phosphorus content of 24.07 mg/kg, available potassium content of 135.73 mg/kg, and pH of 8.13.

The precipitation and average air temperature during the summer maize growing season in 2017 and 2018 are shown in Figure 1. The total precipitation during the growing season was 294.3 mm in 2017 and 398.6 mm in 2018. The proportions of precipitation at different growth stages (seedling, jointing, tasseling, filling, and maturity stage) were 7.1%, 9.6%, 18.0%, 27.6%, and 37.6% in 2017, respectively, and 25.9%, 15.9%, 12.4%, 42.8%, and 3.0% in 2018, respectively. The precipitation was concentrated at the filling and maturity stages in 2017 and at the seedling and tasseling stages in 2018. The range of air temperature in growing season was 11.4°C–33.4°C in 2017 and 13.8°C–31.4°C in 2018, and the average air temperature was 24.1°C and 24.3°C during the two growing seasons in 2017 and 2018, respectively.

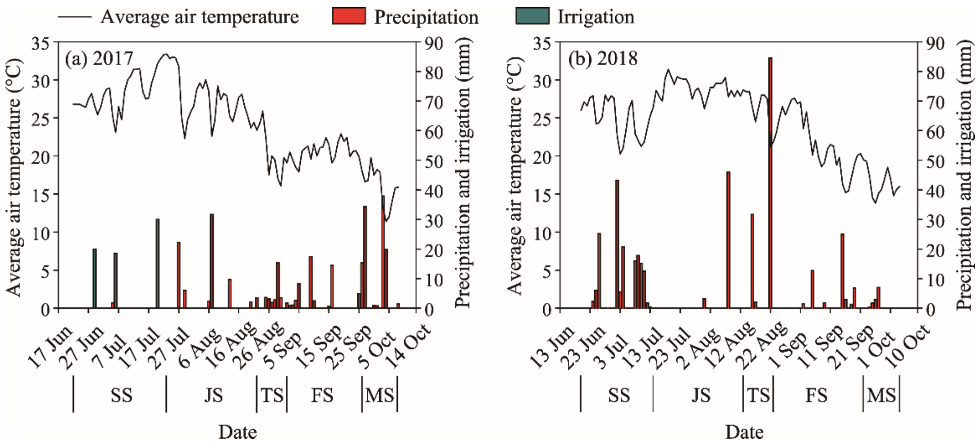

Fig. 1 Meteorological data (average air temperature and precipitation) and irrigation volume during the summer maize growing seasons in 2017 (a) and 2018 (b). SS, seedling stage; JS, jointing stage; TS, tasseling stage; FS, filling stage; MS, maturity stage.

2.2 Experimental design and field management

The field experiment comprised three treatments: conventional flat planting with no mulching (CK; Fig. 2a), RFM (ridge-furrow with ridges mulched and furrows bare; Fig. 2b) and DRFFM (double ridges and furrows full mulching; Fig. 2c). Each treatment had three replicates arranged in a completely randomized design. Before the experiment was carried out, basal fertilizers were

applied to the field at rates of 160 kg/hm^2 of nitrogen, 120 kg/hm^2 of P_2O_5, and 60 kg/hm^2 of K_2O. The field was plowed and divided into plots. Each plot was 4.0 m×4.5 m and was separated by 1 m-wide pathway. The ridge was 0.1 m high and 0.5 m wide for RFM and DRFFM and the furrow was 0.5 m wide for RFM. Ridges were covered with 0.008 mm thick and 0.9 m wide transparent polyethylene film. In the middle of furrows in DRFFM, where two plastic films from adjacent ridges met, a narrow gap was considered as the sowing row (Fig. 2c). After ridges and plastic film were established, summer maize 'zhengdan 958' was sown at the planting density of 66,667 plants/hm^2 with 0.5 m in row spacing and 0.3 m in plant spacing on 23 June 2017 and 20 June 2018, and harvested on 8 October 2017 and 4 October 2018, respectively. When there were three visible leaves, the sick and weak seedlings were removed to ensure that the remaining plants were healthy and growing similarly. Due to the drought at the early growth stage in 2017, each plot was irrigated with 20 mm at the seedling stage (29 June) and 30 mm at the jointing stage (20 July) in 2017 to ensure normal crop growth (Fig. 1). During the two growing seasons, weed control and pesticides application were conducted to maintain relatively healthy crops.

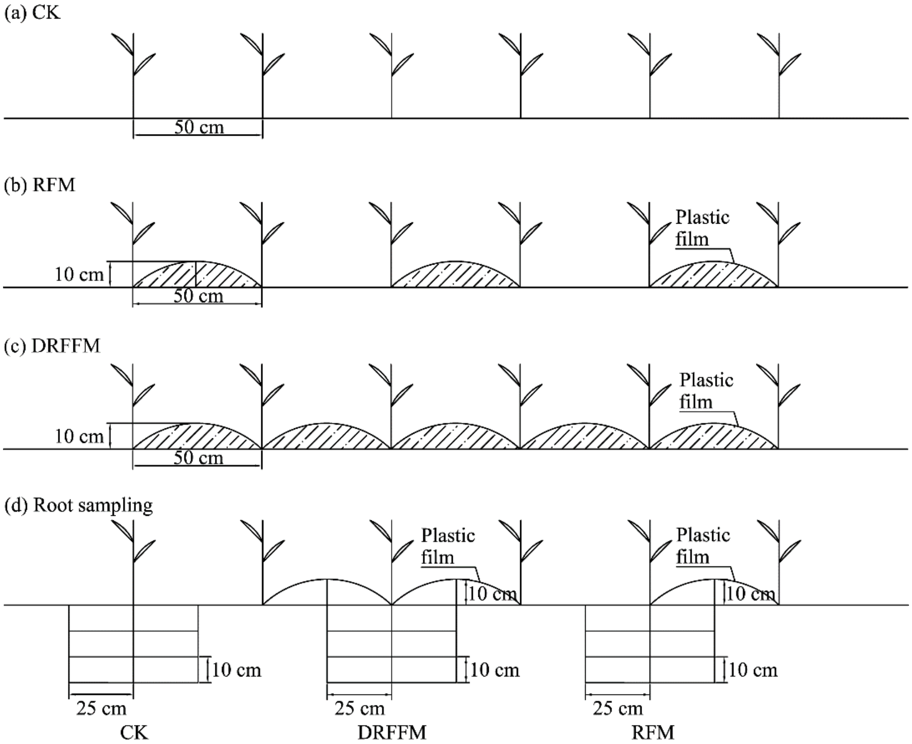

Fig. 2 Schematic diagrams of three planting patterns (a, b, and c) and root sampling (d). CK, flat planting with no mulching; RFM, ridge-furrow with ridges mulching and furrows bare; DRFFM, double ridges and furrows full mulching.

2.3 Sampling and measurements

2.3.1 Soil temperature

Mercury-in-glass geothermo meters with bent stems (Hongxing Thermal Instruments, Wuqiang County, China) were placed in the middle of the ridges and furrows in each plot at depths of 5, 10, 15, 20, and 25 cm. Soil temperature was recorded during 08:00–18:00 (LST) at 2 h intervals after sowing every 15 d in the two growing seasons. The mean daily temperature was calculated using all-day and all-depth readings.

2.3.2 Soil moisture

Before sowing and after harvesting, soil moisture for the 0–200 cm soil profile was determined to calculate the change of SWS throughout each growing season. Soil moisture for 0–100 cm depth was also measured every 15 d from sowing to harvesting to observe the dynamic changes of soil

water content in each season. Soil was sampled at 10 cm intervals using a soil auger between two adjacent plants in the middle of a row. Each sample was replicated three times. Besides, the jointing and filling stages are the key periods of rapid growth and yield formation of summer maize and soil water distribution at these two growth stages is very important for crop growth. In order to investigate the effects of different ridge-furrow mulching systems on soil water distribution in ridges and furrows, we respectively measured soil moisture in ridges and furrows on the first and the seventh day of a continuous no rainfall period after a rainfall event at the jointing and filling stages. The sampling time mentioned above was 36, 42, 87, and 94 d after seedling (DAS) in 2017, and 24, 31, 65, and 72 DAS in 2018. All soil samples were dried at 105°C in an oven to a constant weight to calculate the gravimetric water content.

Soil water storage (SWS, mm) was calculated as:

$$\mathrm{SWS}=\sum_{i=1}^{n}\omega_i\times\gamma\times h\times 10\,, \tag{1}$$

where ω_i is the gravimetric water content (%) at different soil layers; γ is the soil dry bulk density (g/cm^3); h is the soil thickness (cm); and n is the number of soil layers.

2.3.3 Root parameters and aboveground dry matter

Three representative plants were selected from each treatment and the roots were sampled by the soil monolith excavation method (Böhm, 2012; Thidar et al., 2020) at the jointing and filling stages in 2017 and 2018 (Fig. 2d). Considering that more than half of maize root biomass is concentrated in the topsoil layer (Schenk and Jackson, 2002; Fan et al., 2016), we chose the root sampling depth of 40 cm (including 30 cm below the flat ground and 10 cm of ridge height) to minimize the labor on the premise of meeting the research needs. Taking the plant as center, the sampling range was 50 cm (perpendicular to the row)×20 cm (parallel to the row)×40 cm (down from the top of the ridge). Soil samples were dug layer by layer at 10 cm intervals from top to bottom (Fig. 2d). The roots at different soil depths were picked out, cleaned with water, and then imaged by EPSON V900 (Epson, Nagano, Japan). The pictures of roots were analyzed by a WinRHIZO Root analysis system (Regent Instruments Inc., Quebec, Canada) to determine root length at different soil depths, and then roots were dried in an oven at 75°C to a constant weight and to calculate root mass. Moreover, the total root mass and total root length of each plant were calculated by multiplying the measured root biomass in all soil monoliths by two for CK, DRFFM, and RFM.

Three representative plants were randomly selected from each treatment at different growth stages; the aboveground parts were cut off and separated into stem, leaf, and ear and were then cut into small pieces. They were then oven-dried at 105°C for half an hour and at 75°C until a constant weight and then weighed.

2.3.4 Yield, evapotranspiration (ET), and water use efficiency (WUE)

Three rows of summer maize were randomly selected in the middle of each plot for artificial harvest to determine grain yield (at water content of 14%) and yield components including spike length, ear diameter, grains per ear, and 100-grain weight.

Since the groundwater level was below 5 m and each plot had boundaries, recharge, permeation, and runoff were assumed to be negligible. ET (mm) was calculated with the following equation:

$$\mathrm{ET}=\mathrm{P}+\mathrm{I}+W_0-W_1\,, \tag{2}$$

where P is the precipitation (mm); I is the amount of irrigation (mm); and W_0 and W_1 are the SWS (in the soil depth of 0–200 cm) before sowing and after harvesting (mm), respectively.

WUE (kg/(hm^2•mm)) was defined as:

$$\mathrm{WUE}=\mathrm{Y}/\mathrm{ET}\,, \tag{3}$$

where Y is the yield of summer maize (kg/hm^2).

2.4 Data analysis

All data presented are averages of three replicates. We conducted analysis of variance (ANOVA) by SPSS 19.0 (SPSS Inc., Chicago, USA), and determined the significance of differences between treatments by Duncan's multiple range test at P<0.05 level. Figures were created by Origin 8.0

(OriginLab, Northampton, USA) and Auto CAD 2007 (Autodesk Inc., San Rafael, USA).

3 Results

3.1 Soil temperature

3.1.1 Dynamics of soil temperature

The changing of soil temperature for all treatments was affected by air temperature and was almost consistent with the change of air temperature (Figs. 1 and 3). Soil temperature in ridges for DRFFM and RFM had no significant differences with each other and both the values were significantly (P<0.05) higher than that for CK (Fig. 3); while soil temperature in furrows for DRFFM and RFM was similar to that for CK. Compared with CK, the average soil temperature in ridges was 3.9°C and 4.3°C higher in DRFFM, and 2.7°C and 3.0°C higher in RFM in 2017 and 2018, respectively.

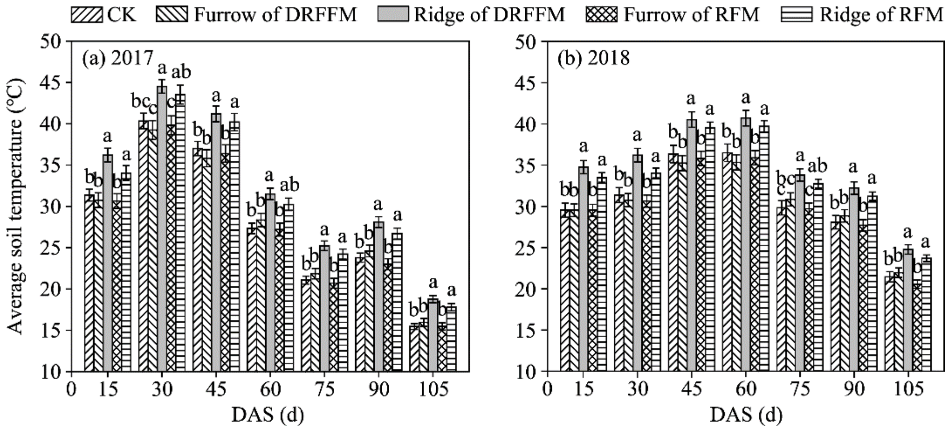

Fig. 3 Average soil temperature at depth of 5–25 cm for different treatments during the growing seasons in 2017 (a) and 2018 (b). DAS, days after sowing. The furrow of DRFFM (or RFM) represents the average soil temperature in furrows of DRFFM (or RFM); the ridge of DRFFM (or RFM) represents the average soil temperature in ridges of DRFFM (or RFM). Different lowercase letters at the same time indicate significant differences among treatments at P<0.05 level. Bars mean standard errors.

3.1.2 Diurnal variations of soil temperature

From 08:00 to 18:00, the average soil temperature at 5–25 cm depth in ridges was higher than that under CK and the difference became larger after 12:00 (Fig. 4), indicating that mulching film significantly increased soil temperature and this promotion was more significant in the afternoon. Moreover, except the filling stage in 2017, soil temperature in ridges greatly exceeded the maximum temperature of 30.0°C that is suitable for maize growth (Lobell et al., 2013). The daily average soil temperature in ridges for DRFFM and RFM was 44.5°C and 43.5°C at the jointing stage, respectively, and 25.2°C and 24.2°C at the filling stage, respectively, in 2017; while in 2018, it was 34.8°C and 33.5°C at the jointing stage, respectively, and 33.8°C and 32.7°C at the filling stage, respectively.

3.2 SWS

3.2.1 SWS at different growth stages

SWS of 0–100 cm soil depth for CK, RFM, and DRFFM fluctuated with the precipitation distribution in the two growing seasons. The differences of SWS among the three treatments were significant at the seedling (15 DAS), tasseling (60 DAS), filling (75 and 90 DAS) and maturity (105 DAS) stagesin 2017 and 2018 (Fig. 5). At the jointing stage, SWS in DRFFM was larger than in RFM, but the difference was not significant. SWS was the highest for DRFFM, followed by RFM and CK. It was 14.7% and 14.2% higher for DRFFM than for CK in 2017 and 2018, respectively. Correspondingly, SWS for RFM was 8.1% and 8.2% higher than that for CK in 2017 and 2018, respectively.

3.2.2 SWS in furrows and ridges

In the absence of rainfall and irrigation, SWS in both ridges and furrows decreased over time.

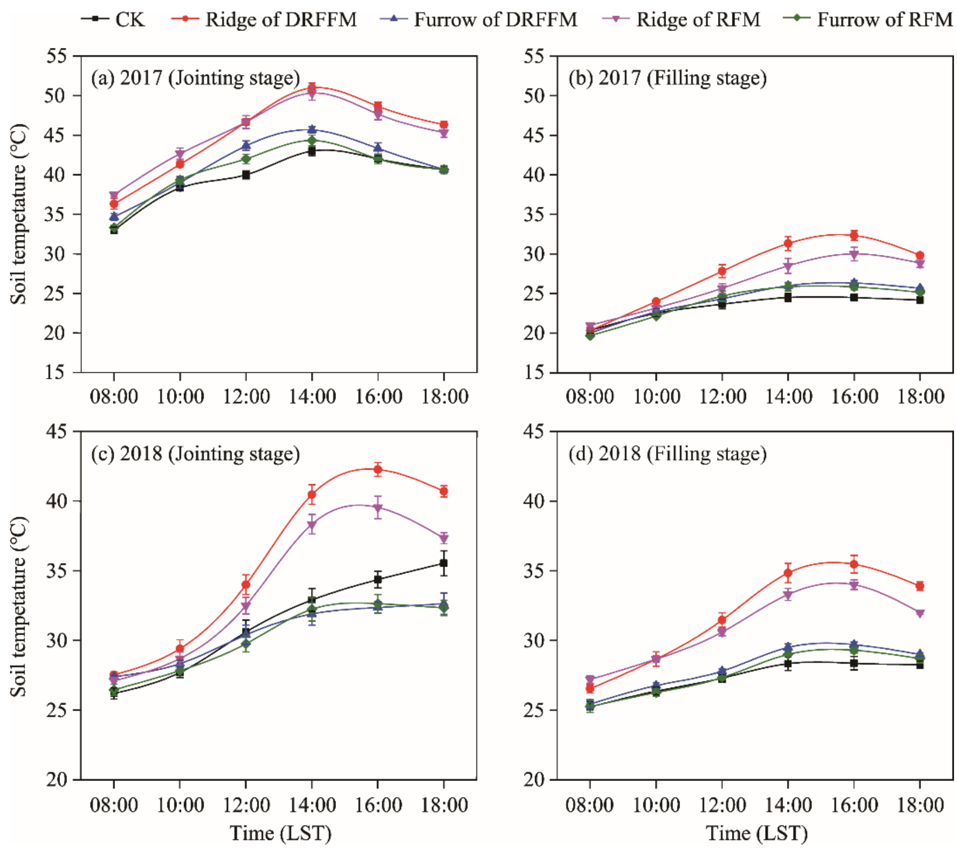

Fig. 4 Diurnal variations of average soil temperature at 5–25 cm depth at the jointing (a, c) and filling stages (b, d) in 2017 and 2018 for different treatments. Bars represent the standard errors.

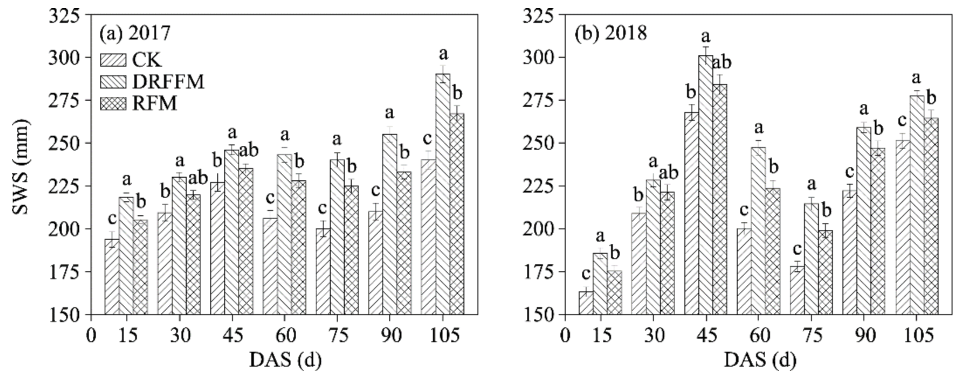

Fig. 5 Dynamics of soil water storage (SWS) at depth of 0–100 cm for CK, DRFFM, and RFM treatments in 2017 (a) and 2018 (b). Different lowercase letters at the same time indicate significant differences among treatments at *P*<0.05 level. Bars represent the standard errors.

Meanwhile, the difference of SWS between ridges and furrows also varied, which mainly occurred at the soil depth of 0–50 cm (Fig. 6). On the first day after the rainfall event, SWS to a depth of 50 cm in furrows was 7.7, 5.0, 9.8, and 4.8 mm higher than that in ridges for DRFFM at the jointing stage in 2017, filling stage in 2017, jointing stage in 2018, and filling stage in 2018, respectively; similarly, SWS in furrows was 13.9, 8.4, 11.3, and 8.2 mm higher than that in ridges for RFM at these four growth stages, respectively. On the seventh day after the rainfall event, SWS in furrows was 9.5, 5.6, 15.9, and 4.9 mm lower than that in ridges for DRFFM at these four growth stages, respectively; while SWS in furrows was still 9.8, 8.0, 11.4, and 7.2 mm higher than that in ridges for RFM at these four growth stages, respectively.

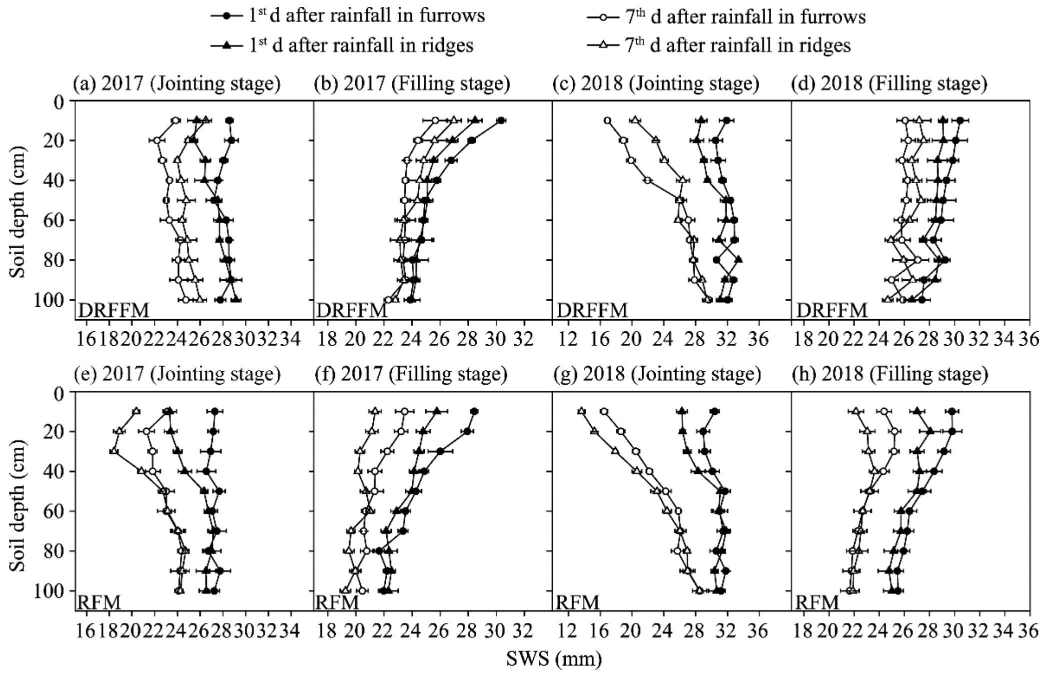

Fig. 6 Dynamics of SWS at 0–100 cm depth in furrows and ridges on the first and the seventh day after the rainfall event for DRFFM and RFM at the jointing and filling stages in 2017 (a, b, e, f) and 2018 (c, d, g, h). The first and the seventh day after the rainfall event was 12 July and 3 August at the jointing stage, respectively, and was 17 September and 23 September at the filling stage, respectively, in 2017. The first and the seventh day after the rainfall event was 13 July and 20 July at the jointing stage, respectively, and was 23 August and 30 August at the filling stage, respectively, in 2018. Bars represent the standard errors.

3.3 Root growth

3.3.1 Roots in different planting patterns

Root mass and root length varied significantly under different planting patterns, growth stages, and growing years (Table 1). Compared with CK, root mass at the jointing stage in DRFFM and RFM non-significantly increased by 1.5% and 10.4%, respectively, in 2017, and significantly increased by 14.3% and 9.9%, respectively, in 2018. At the filling stage, DRFFM decreased root mass by 4.6% and 7.4% in 2017 and 2018, respectively; while RFM increased it by 21.1% and 17.4% in 2017 and 2018, respectively, with significant differences, compared with CK. Root length was significantly increased in both DRFFM and RFM compared with CK, and the increasing effect of DRFFM was more significant. Across the two growing seasons, root length at the jointing and filling stages was respectively increased by 75.4% and 58.7% in DRFFM, and 20.6% and 30.2% in RFM, relative to CK. Root mass and length for each treatment at the filling stage increased compared with those at the jointing stage, but the degrees of increase were different. The increased proportions of root mass and length at the filling stage relative to the jointing stage over the two growing seasons were respectively 42.8% and 94.9% in DRFFM, 63.2% and 115.1% in CK, and 76.7% and 132.1% in RFM.

3.3.2 Vertical root distribution

Root mass in ridges was 538.4% and 422.4% significantly higher in DRFFM than in RFM at the jointing and filling stages across the two growing seasons, respectively (Fig. 7). Compared with CK, root mass of 0–10, 10–20, and 20–30 cm soil layers was higher in RFM and lower in DRFFM except 0–10 cm soil layer at the jointing stage in 2018. Compared with CK, RFM increased root mass by 6.6%, 19.1%, and 32.6% at the jointing stage in 0–10, 10–20, and 20–30 cm soil layers, respectively, and by 15.0%, 21.1%, and 31.7% at the filling stage, respectively. DRFFM decreased root mass in 0–10, 10–20, and 20–30 cm soil layers by 5.2%, 33.8%, and 31.8% at the jointing stage, respectively, and by 22.0%, 38.2%, and 33.7% at the filling stage, respectively.

Table 1 Root mass and root length under different planting patterns at the jointing and filling stages in 2017 and 2018

Year	Treatment	Root mass (g/plant)		Increased root mass (filling-jointing) (%)	Root length (m/plant)		Increased root length (filling-jointing) (%)
		Jointing stage	Filling stage		Jointing stage	Filling stage	
2017	CK	6.7±0.3^{a}	10.9±0.4^{a}	62.7±0.6^{b}	119.2±4.3^{c}	247.1±8.9^{c}	107.3±2.8^{b}
	DRFFM	6.8±0.2^{a}	10.4±0.4^{b}	52.9±0.8^{c}	194.2±6.8^{a}	382.1±15.6^{a}	96.8±3.3^{c}
	RFM	7.4±0.3^{a}	13.2±0.4^{a}	78.4±0.9^{a}	137.9±4.1^{b}	311.5±9.7^{b}	125.9±1.6^{a}
2018	CK	9.1±0.3^{b}	14.9±0.6^{a}	63.7±1.0^{a}	137.1±4.5^{c}	305.6±9.6^{c}	122.9±2.5^{b}
	DRFFM	10.4±0.4^{a}	13.8±0.7^{b}	32.7±6.4^{b}	257.7±9.7^{a}	497.2±20.4^{a}	92.9±0.9^{c}
	RFM	10.0±0.4^{a}	17.5±0.5^{a}	75.0±1.3^{a}	172.2±4.0^{b}	410.4±14.4^{b}	138.3±3.5^{a}

Significance (F value)

Year (Y)	Growth stage (G)	Planting pattern (P)	Y×G	Y×P	P×G	Y×P×G
12.7**	537.7**	9.7**	175.3**	0.6^{ns}	15.2**	0.3^{ns}
136.1**	1044.4**	227.6**	33.6**	6.5**	22.6**	1.0^{ns}

Note: CK, flat planting with no mulching; DRFFM, double ridges and furrows full mulching; RFM, ridge-furrow with ridges mulching and furrows bare. Mean±SD. Different lowercase letters within a column in the same year indicate significant differences among treatments at P<0.05 level. **, P<0.05 level; ns, non-significant.

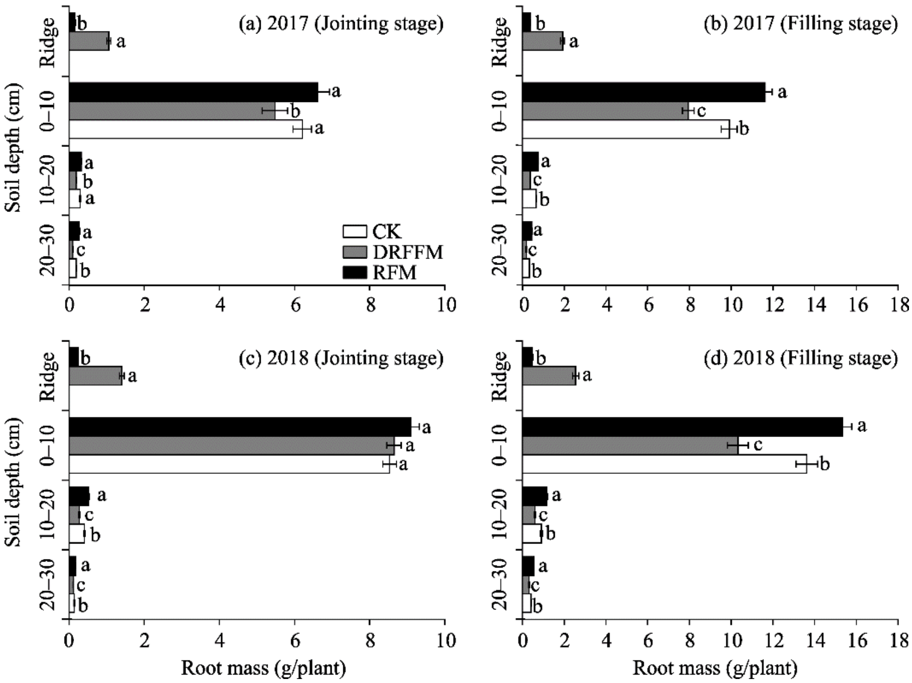

Fig. 7 Vertical distribution of root mass at the jointing and filling stages for CK, DRFFM, and RFM treatments in 2017 (a, b) and 2018 (c, d). Different lowercase letters within the same soil depth indicate significant differences among treatments at P<0.05 level. Bars mean standard errors.

Root length in ridges was 619.6% and 514.2% significantly higher in DRFFM than in RFM at the jointing and filling stages across the two growing seasons, respectively (Fig. 8). Root length in 0–10, 10–20, and 20–30 cm soil layers for DRFFM was significantly lower than that for CK except the 0–10 cm layer at the filling stage in 2017. Root length of 0–10 cm layer for RFM was non-significantly larger than that for CK except at the filling stage in 2018. In 2017, root length in 10–20 and 20–30 cm soil layers for RFM was significantly higher than that for CK except for 20–30 cm soil layer at the jointing stage. Compared with CK, DRFFM decreased root length in 0–10, 10–20, and 20–30 cm soil layers by 9.9%, 9.1%, and 14.7% at the jointing stage, respectively, and by 19.1%, 20.5%, and 18.2% at the filling stage, respectively, across the two growing seasons. RFM treatment increased root length in the three soil layers by 0.6%, 51.5%, and 19.6% at the jointing stage, respectively, and

by 11.2%, 46.9%, and 30.0% at the filling stage, respectively.

Besides, although DRFFM had more root mass at the jointing stage and longer root length at both the jointing and filling stages relative to CK within the sampling depth, a considerable portion of root mass and length was in the ridge soil. Removing the root mass and length in the ridge soil, root mass and root length in 0–30 cm layer for CK were lower than those for RFM and higher than those for DRFFM at the jointing and filling stages in 2017 and 2018.

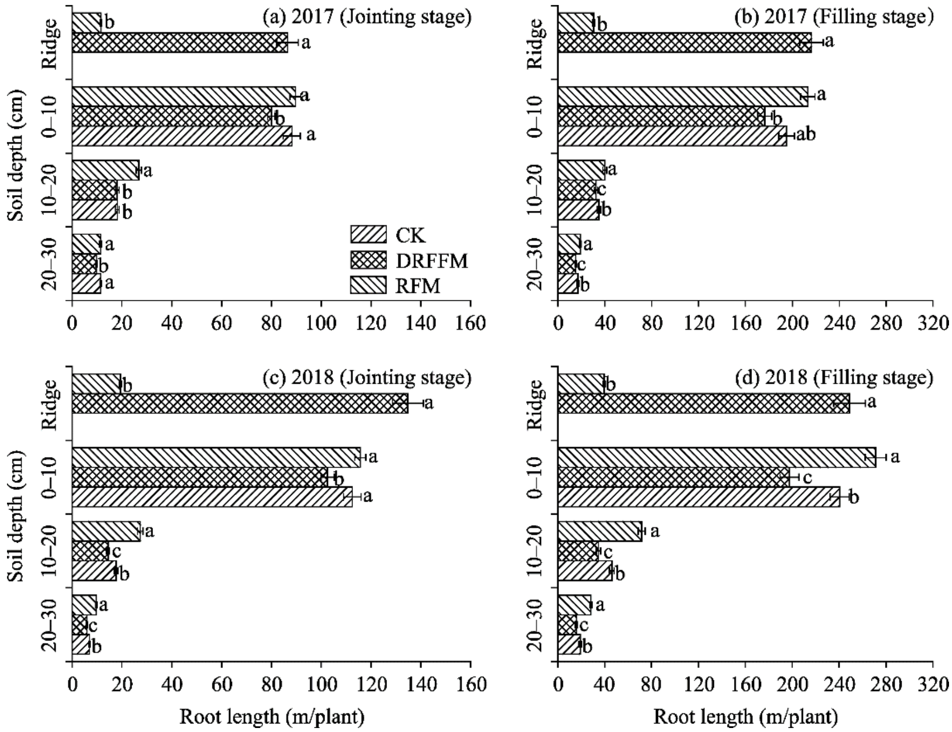

Fig. 8 Vertical distribution of root length at the jointing and filling stages for CK, DRFFM, and RFM treatments in 2017 (a, b) and 2018 (c, d). Different lowercase letters within the same soil depth indicate significant differences among treatments at $P<0.05$ level. Bars mean standard errors.

3.4 Aboveground dry matter

The dry matter of stem and leaf first increased and then decreased with the growth process, and reached the maximum value at the filling stage in the two growing seasons (Fig. 9). The aboveground dry matter reached the peak at the maturity stage. The differences among treatments at the same growth stage varied in different growing seasons. In 2017, compared with CK, the dry matter of stem, leaf, ear, and aboveground part was decreased by 8.6%–19.2%, 5.2%–16.6%, 15.7%–25.6%, and 6.6%–18.8%, respectively in DRFFM and the differences were significant at most growth stages. In 2018, DRFFM significantly increased the dry matter of stem, leaf, ear, and aboveground part from the seedling to tasseling stage except leaves at the tasseling stage and significantly decreased them at the filling and maturity stages, relative to CK. Aboveground dry matter in DRFFM increased by 13.6%–53.5% from the seedling to tasseling stage and decreased by 13.0%–14.5% from the filling to maturity stage in 2018. RFM treatment increased the dry matter of stem, leaf, ear, and aboveground part by 2.1%–16.3%, 2.5%–15.8%, 10.6%–15.4%, and 2.4%–12.7% in 2017, respectively, and by 6.5%–37.1%, 4.7%–30.1%, 13.0%–79.9%, and 10.6%–32.5% in 2018, respectively, with significant differences at most growth stages in the two studied years.

3.5 Grain yield and WUE

Compared with CK, all of yield component factors (including spike length, spike diameter, kernel rows number (KRN), grains per row and grains per spike, and 100 grain weight) were lower in DRFFM and higher in RFM. The difference between CK and DRFFM was only significant in 100

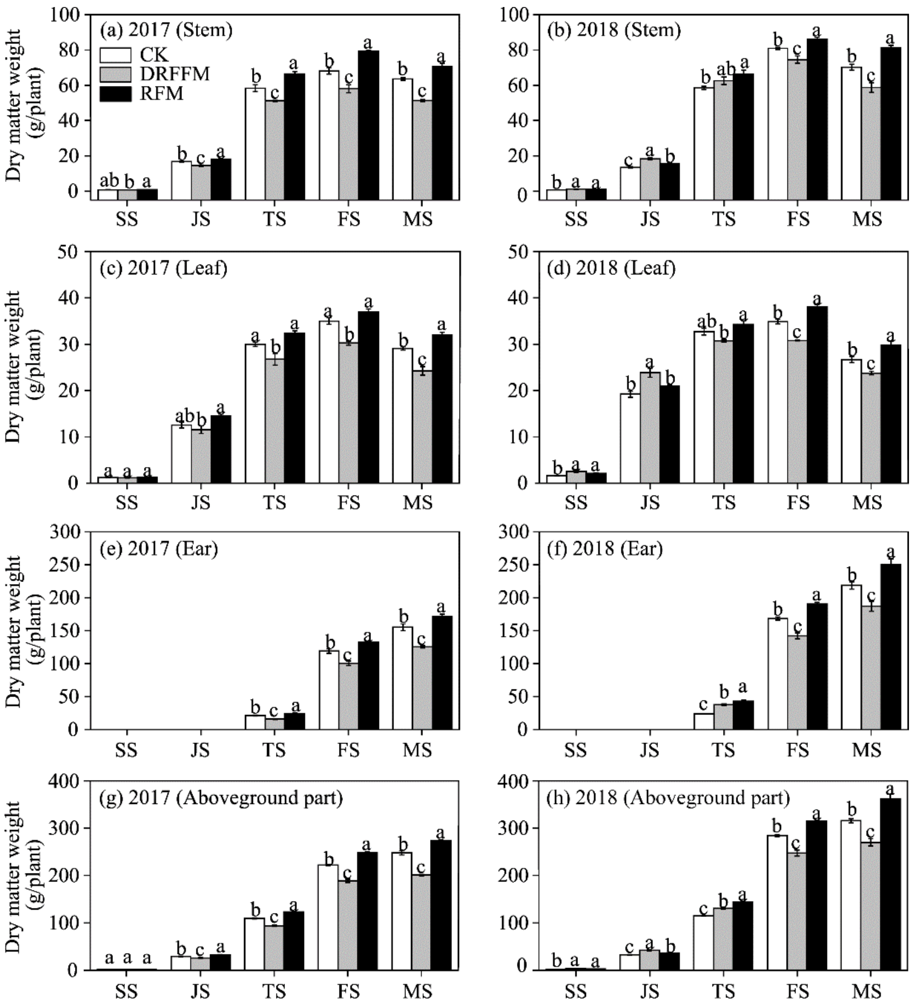

Fig. 9 Dry matter of stem, leaf, ear, and aboveground part for CK, DRFFM, and RFM treatments in 2017 (a, c, e, g) and 2018 (b, d, f, h). Different lowercase letters within the same growth stage indicate significant differences among treatments at *P*<0.05 level. Bars mean standard errors.

grain weight in 2018, and the difference between CK and RFM was significant in grains per row and grains per spike in 2018 and spike length in 2017 and 2018 (Table 2). Compared with CK, grain yield in DRFFM was non-significantly 12.5% lower in 2017 and significantly 16.1% lower in 2018. Grain yield in RFM was non-significantly 10.4% higher in 2017 and significantly 16.8% higher in 2018, compared with CK. The values of ET for DRFFM and RFM were both significantly lower than that for CK. The mean ET for CK was 9.8% higher than that for DRFFM and 7.1% higher than that for RFM across the two growing seasons. WUE for CK was non-significantly 6.8% higher than that for DRFFM and significantly 22.5% lower than that for RFM across the two growing seasons.

4 Discussion

Ridge-furrow mulching systems have great impacts on soil water and heat conditions, which affect root morphology, root distribution, and crop yield.

4.1 Soil temperature

The warming effect of plastic film mulching on soil has been widely confirmed (Wang et al., 2018). Our experiment also found that soil temperature was increased in ridges under film mulching (Fig. 3). However, excessively raising soil temperature is not always beneficial for crop growing in regions with sufficient accumulated temperature. Within a reasonable range, elevated soil

Table 2 Yield components, grain yield, ET, and WUE for CK, DRFFM and RFM treatments in 2017 and 2018

Year	Treatment	Spike length (cm)	Spike diameter (mm)	KRN	Grains /row	Grains /spike	100 grain weight (g)	Grain yield (kg/hm^2)	ET (mm)	WUE (kg/(hm^2•mm))
2017	CK	17.2±0.5^b	49.1±0.9^a	14.0±0.8^a	38.9±0.7^a	543.3±28.6^a	28.1±0.9^a	7231.7±522.8^{ab}	360.7±4.2^a	20.0±1.1^b
	DRFFM	17.1±0.6^b	47.9±1.0^a	13.5±0.6^a	36.5±3.0^a	497.3±63.7^a	26.3±0.6^a	6330.6±695.1^b	332.9±7.7^b	18.2±0.9^b
	RFM	18.8±0.1^a	50.5±0.8^a	15.5±0.5^a	38.6±0.9^a	599.0±29.0^a	28.9±1.0^a	7986.7±430.7^a	341.1±3.9^b	23.4±1.3^a
2018	CK	17.2±0.5^b	49.2±1.1^a	14.8±0.5^a	39.5±0.8^b	584.3±16.3^b	33.4±1.3^a	8504.6±382.0^b	362.0±8.3^a	23.5±0.9^b
	DRFFM	16.5±0.2^b	47.7±1.0^a	14.4±0.4^a	36.9±1.0^b	529.3±15.9^b	30.2±0.7^b	7139.5±223.9^c	318.8±5.5^b	22.4±0.7^b
	RFM	18.9±0.5^a	48.7±1.0^a	16.0±0.6^a	42.9±0.8^a	686.3±25.2^a	33.4±1.1^a	9933.4±483.1^a	330.2±7.6^b	30.1±1.5^a

Note: KRN, kernel rows number; Grains/row, grains per row; Grains/spike, grains per spike; ET, evapotranspiration; WUE, water use efficiency. Mean± SD. Different lowercase letters within a column indicate significant differences among treatments at $P<0.05$ level.

temperature can increase the effective accumulated temperature (Chen et al., 2012), accelerate crop growth (Mo et al., 2016), and increase grain yield (Wang et al., 2018). When temperature exceeds the suitable range, it will become unhelpful or even harmful to crops. Lobell et al. (2013) pointed out that maize yield had a negative response when temperature accumulation exceeded 30.0°C. Yu et al. (2018) found that plastic film had no positive effect on maize in dry lands of China when temperature exceeded 24.0°C. In this study, the significantly increased ridge soil temperature above 30.0°C for DRFFM and RFM treatments (Figs. 3 and 4) may be detrimental to the healthy growth of crops (Morales et al., 2003; Yin et al., 2019).

4.2 SWS

SWS could be affected by precipitation (Han et al., 2014), planting pattern (Zhou et al., 2009), and crop consumption (Zhang et al., 2019a). In the present study, DRFFM and RFM significantly increased SWS in furrows benefiting from ridge-furrow with plastic mulching collecting rainwater and increasing infiltration, compared with CK (Figs. 5 and 6), which was same as previous researches (Wu et al., 2017; Gu et al., 2018; Gao et al., 2019).

Different from traditional flat farming, ridge-furrow with plastic film mulching systems has greatly changed the soil surface shape and soil aeration, which inevitably changed the horizontal distribution and redistribution of soil water. Previous studies have focused more on ridge-furrow mulching systems increasing SWS in furrows, but little attention was paid to the changes of soil water in ridges next to crops (Wang et al., 2016; Wang et al., 2018). In the present study, SWS was lower in ridges than in furrows for DRFFM and RFM shortly after the rainfall event (Fig. 6). This is because that the furrows served as the infiltration areas for the collected rainwater (Yin et al., 2015). After a period of no rainfall and irrigation, SWS in ridges was higher than that in furrows for DRFFM, which was different from the case that SWS was lower in ridges than in furrows for RFM (Fig. 6). This difference was mainly attributed to the structural difference between DRFFM and RFM (Wu et al., 2017). Because of the narrower furrows in DRFFM relative to RFM (Ren et al., 2016), more collected rainwater was concentrated near ridges, moved upward driven by solar radiation, and eventually accumulated in ridges under plastic film (He et al., 2018; Zhang et al., 2019b). At the same time, soil water in furrows decreased for evaporation and crop water consumption, resulting in lower water content in furrows than in ridges for DRFFM. Although DRFFM prevented more water evaporation due to the larger mulching area (Zhao et al., 2014), some of the water was transferred to ridges (Fig. 6). Because the roots of summer maize tended to grow in where there is more soil moisture (Qi et al., 2015; Yin et al., 2015), the higher SWS in ridges for DRFFM might induce more roots in ridges.

4.3 Root distribution

Root biomass and its distribution are both important to crop growth. Ridge-furrow mulching systems affecting root mass and length has been widely documented (Yin et al., 2015; Gu et al., 2016; Thidar et al., 2020), but the vertical root distribution under different ridge-furrow mulching systems is not well understood. In this study, RFM and DRFFM increased root mass at the jointing and filling stages across the two growing seasons except the DRFFM at the filling stage, which was

not completely consistent with previous studies about ridge-furrow mulching systems increasing root mass. Some studies stated that higher soil temperature decreased root enzyme activity and accelerated root aging (Bu et al., 2013; Qin et al., 2018). The less root mass for DRFFM at the filling stage may be due to the accelerated root senescence caused by high soil temperature in ridges (Gao et al., 2014). In addition, the healthy and strong root system at the filling stage is an important support to ensure nutrient absorption and maintain long-term high plant activity to achieve high yield (Gao et al., 2014; Zhao et al., 2017). In our study, RFM had the largest increased proportions of root mass and length at the filling stage relative to the jointing stage, followed by CK and DRFFM with significant differences, which showed that DRFFM lacked power to promote root growth and even hindered root growth during the filling stage.

Moreover, due to more abundant water and heat in the ridge soil, DRFFM increased root mass and length in ridges but decreased them in 0–30 cm soil layer beneath the flat ground compared with CK. This may be helpful at the early growth stage, but the closed soil spaces, nutrient deficiencies, and high temperature in the ridge soil may damage root growth at the late growth stages. Meanwhile, the loss of deep roots may reduce the utilization of deep soil moisture and nutrients and lodging resistance (Morales et al., 2003). In contrast, RFM increased root mass and length in ridges in 0–30 cm soil layer compared with CK at the jointing and filling stages, which may be beneficial to the dry matter accumulation at the early stages and grain formation at the later growth stages.

4.4 Aboveground dry matter, grain yield, and WUE

Many studies have found that ridge-furrow with plastic film mulching systems significantly improves soil hydrothermal conditions, and increases aboveground dry matter, grain yield, and WUE of maize (Liu et al., 2014), potato (Zhao et al., 2014), and oat (Qi et al., 2015). In this study, DRFFM decreased the aboveground dry matter of summer maize in two growing seasons except for the seedling and jointing stages in 2018. This result was different from the conclusion that DRFFM increased the aboveground dry matter (Liu et al., 2014; Ren et al., 2016). In 2017, the almost complete coverage for DRFFM aggravated the drought and high temperature stress and reduced the early aboveground dry matter. However, the relatively uniform rainfall in 2018 highlighted the rain collection effect of DRFFM, with an increase of early aboveground dry matter. At the later growth stages, root proliferation and limited nutrients in ridges and poor soil aeration in DRFFM accelerated root senescence and impeded dry matter accumulation (Bu et al., 2013; Qin et al., 2018). RFM increased the dry matter of stem, leaf, and ear in both growing seasons. Although RFM also excessively increased soil temperature in ridges, only a small amount of roots grew in ridges, avoiding the adverse effects of high temperature, nutrient shortage, and poor aeration on root growth (Zhang et al., 2015). In addition, RFM also significantly increased soil moisture in furrows, which was conducive to crop growth. In summary, RFM had more advantages than disadvantages for crop growth, ultimately increasing the aboveground dry matter.

DRFFM treatment reduced ET, grain yield, and WUE, while RFM reduced ET and increased grain yield and WUE. This was different from the previous conclusion that DRFFM increased grain yield and WUE in arid and cold regions (Wang et al., 2018). It may be because water deficit and insufficient accumulated temperature are the main factors restricting crop growth in arid and cold regions in the past few years, but with climate warming, the local agriculture regions in the Loess Plateau usually have relatively sufficient accumulated temperature (Gao et al., 2014; Zhang et al., 2018).

5 Conclusions

Both DRRFM and RFM increased soil temperature in ridges and SWS in furrows. DRFFM treatment prevented soil water evaporation in ridges, resulting in higher soil water content in ridges than in furrows after a period of no water input. Both DRFFM and RFM increased root mass and length at the jointing and filling stages except for DRFFM decreasing root mass at the filling stage. DRFFM treatment slowed down root growth at the later growth stages. RFM treatment increased root mass and length in 0–30 cm soil layer, while DRFFM decreased root mass and length in 0–30 cm soil layer but increased them in ridges. Aboveground dry matter, grain yield, and WUE were

decreased in DRFFM and increased in RFM. Therefore, RFM is recommend as a viable option for summer maize in the regions with water shortage and sufficient accumulated temperature.

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